

## 3.5. Japan

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### 3.5.1. Introduction

It is considered that a molten salt reactor (MSR) based on  $^{233}\text{U}$ -Th fuel cycle is one of the best reactor system from the standpoint of neutron economy and it is free from fuel fabrication, therefore, several studies have been made for incinerating minor actinides (MA) produced in a light water reactor (LWR) using MSR [1-3]. In 1995, IAEA organized a Coordinated Research Program (CRP) on "Potential of Th-based Fuel Cycles to Constrain Pu and to Reduce Long-term Toxicities". The purpose of the study is to look for the best reactor system in reducing the large stockpile of plutonium both from a conventional reactor (reactor-grade plutonium) and nuclear disarmament using the present and near-term reactor technology. We decided to study a MSR because of the reason stated above.

The first stage of the study was to make a benchmark calculation of the isotope composition, cross-sections and neutron fluxes for a typical PWR cell loaded with (Pu-Th) $\text{O}_2$  fuel as a function of fuel burnup until 60 MWD/kg and make comparisons of the effect of different computing system and data basis applied in each participants. The results are reported in [4] and the conclusion was the results of each participant agreed reasonably well. In the second stage, each participant is asked to analyze and to compare the main performance parameters of the Th-based fuel cycle options aiming to the objective of the CRP. A part of the study was reported in [5] and at the IAEA RCM (Research Coordinated Meeting) at Taejon in October 1999, however, we recalculated the fuel burnup to meet the standard of 300 day operation in a year and made the calculation of toxicities accordingly.

### 3.5.2. Reactor model

The reactor model was taken based on FUJI model [6], which consists of graphite moderator columns with a circular fuel salt channel as shown in Fig. 3.5.1. The atomic number densities of both reactor-grade plutonium and weapons-grade plutonium are shown in Table 3.5.1. According to preliminary calculations for  $V_F/V = 0.10$  (radius of the fuel zone  $r = 6.64$  cm) where  $V_F$  is the fuel volume and  $V$  is the total volume of a cell, the fuel salt composition was determined as  ${}^7\text{LiF}\text{-BeF}_2\text{-ThF}_4\text{-PuF}_3 = 72\text{-}16\text{-}11.8\text{-}0.2$  mol%. Then to see the effect of  $V_F/V$ ,  $V_F/V$  was changed to 0.05 ( $r = 6.64$  cm) and 0.20 ( $r = 9.3946$  cm) and the case that gives the same  $k_{\text{inf}}$  as the case with  $V_F/V = 0.1$  was looked for. Although for  $V_F/V = 0.10$  and the fuel salt composition of  ${}^7\text{LiF}\text{-BeF}_2\text{-ThF}_4\text{-PuF}_3 = 72\text{-}16\text{-}11.8\text{-}0.2$  mol%, the burning of plutonium was most favorable, this case gave the positive temperature coefficient of  $dk/dT = 3.2 \times 10^{-5} \Delta k/k$  from 839 K to 977 K. On the other hand, for the case with  $V_F/V = 0.2$ , and the fuel salt composition of  ${}^7\text{LiF}\text{-BeF}_2\text{-ThF}_4\text{-PuF}_3 = 72\text{-}16\text{-}11.4\text{-}0.6$  mol%, the temperature coefficient was  $-6.5 \times 10^{-6} \Delta k/k$ . Therefore, we selected the case  $V_F/V = 0.2$  which gives  $k_{\text{inf}} = 1.156$  for reactor-grade plutonium. As for the case weapons-grade plutonium, the same  $V_F/V$  and the fuel salt composition of  ${}^7\text{Li}\text{-BeF}_2\text{-ThF}_4\text{-PuF}_3 = 72\text{-}16\text{-}11.8\text{-}0.2$  was selected which gives  $k_{\text{inf}} = 1.156$  though the temperature coefficient was  $+1.66 \times 10^{-5} \Delta k/k$  because of the positive density coefficient (the fuel temperature coefficient was  $-6.45 \times 10^{-6} \Delta k/k$ ). It was assumed that the reactor consisted of 19 columns of the hexagonal graphite moderator 2 m high shown in Fig. 3.5.1. The effective radius of the core was 91.6 cm. The core was surrounded with a 5 cm thick fuel salt path and 100 cm thick graphite reflector in each direction as shown in Fig. 3.5.2. For this

model, two-dimensional (2D) calculation for the fresh fuel core gave  $k_{\text{eff}} = 1.0219$  and almost same  $k_{\text{eff}}$  for the case of  $\sim 100$  MWD/kg of burnup. Therefore, it is enough to calculate the change in  $k_{\text{inf}}$ , since in the case of MSR, the flux distribution during the burnup should be the same so long as the  $k_{\text{eff}}$  is kept  $\sim 1.00$ . It is assumed that the reactor power was 200 MWth and the fuel salt composition was same throughout the reactor because of the mixing of the fuel salt. For this model, the fuel salt volume inside the reactor vessel (core and fuel salt path surrounding the core) is  $1.939 \times 10^6 \text{ cm}^3$ . It was also assumed that the fuel volume ratio inside the reactor vessel and outside of the vessel was 1:1. Therefore, the total fuel volume was  $3.878 \times 10^6 \text{ cm}^3$  and the average power density was  $51.6 \text{ W/cm}^3$ . Since it is assumed that the reactor is operated 300 days annually, in the actual calculation, it was assumed that the reactor was operated 365 days with the power of  $51.6 \times (300/365) = 42.4 \text{ W/cm}^3$  of power density instead. Plutonium of the same isotopic compositions as the initial ones was continuously added to keep  $k_{\text{eff}} \sim 1.00$ . In the actual calculation, the fuel salt was added with small time interval so that the  $k_{\text{inf}}$  is kept between 1.158 and 1.130. The existence of  $^{135}\text{Xe}$  was totally neglected. The average temperature of the core during the calculation was assumed to be 900K.

### 3.5.3 Calculation of fuel depletion

The burnup calculation was carried out with SWAT code system [7] and the 2D calculation was carried out with SRAC [8] code. As stated in the previous section, the fresh plutonium was fed continuously so that  $k_{\text{inf}}$  was kept between 1.158 and 1.13. The quantities and the time intervals were determined with trial and error. Actually, the calculation of reactor-grade plutonium until 10 years was carried out with the power density of  $51.6 \text{ W/cm}^3$  up to 3000 days and normalized to 10 years so that the same MWD/kg was attained. This assumption should be appropriate except for  $^{241}\text{Pu}$  whose half-life is  $\sim 13$  years, and this was confirmed by the calculation of weapons-grade plutonium at 10 years. Therefore, we adopted the method because of the computation economy. Also, the calculation for reactor-grade plutonium after 15 years was carried out with the different computer system (with the same computing system) and small discrepancy existed in some isotopes, this effect was not serious.

The quantities of the added plutonium are shown in Table 3.5.2 for reactor-grade plutonium and Table 3.5.3 for weapons-grade plutonium. The values at 0 year mean the initially loaded plutonium. The changes in  $k_{\text{eff}}$  are shown in Figs 3.5.3 and 3.5.4 for reactor-grade plutonium and weapons-grade plutonium, respectively. The minima for  $k_{\text{inf}}$  after  $\sim 15$  years are a little less than 1.13, the reason of which is attributed to the use of the different computer system. The changes in atomic number densities are shown in Figs 3.5.5 and 3.6.6 for reactor-grade plutonium and weapons-grade plutonium, respectively. In the case of MSR, it is possible to continue the calculation indefinitely by adding certain amount of plutonium to maintain  $k_{\text{eff}} \sim 1$ , though in reality if we add too much plutonium, plutonium would not become soluble. Therefore we arbitrary determined to finish the calculation 10 year and 20 year of burnup. These values correspond to  $\sim 104$  MWD/kg and  $\sim 208$  MWD/kg for the initially loaded heavy metal (5.77 t). The depletion of thorium was not supplemented, though the amount of the depletion was  $\sim 11.5\%$ .

The amount of plutonium at the end of each time interval, fissile percent of plutonium and the quantities of  $^{233}\text{Pa} + ^{233}\text{U}$  produced are also shown in Tables 3.5.2 and 3.5.3. The amount of the loaded and the burned plutonium at 10 years and 20 years are shown in these tables. In the case of reactor-grade plutonium, the quantity of  $^{233}\text{Pa} + ^{233}\text{U}$  is going to saturate towards the end of 20-year period. The quantity of  $^{239}\text{Pu}$  shows minimum at about 11 years, then it

increases again. Other plutonium isotopes increase monotonically and the fissile percent of plutonium decreases though the rate is very slow at the end of 20 years. Since the fissile percent is ~ 30% and it includes a large amount of  $^{241}\text{Pu}$  which decays with the half-life of ~ 13 years, the quality of plutonium is very poor. However, the quantity of the burned plutonium is not large, 1.48 times of the initially loaded plutonium in 10 years and 3.43 times of that in 20 years.

In the case of weapons-grade plutonium, the atomic number densities of all the plutonium isotopes monotonically increase and fissile percent of plutonium shows minimum at 9.43 years and then it increases again though the rate of increase is very slow. It is impossible to degrade the fissile percent less than ~ 60%, and if the decay of  $^{241}\text{Pu}$  is taken into account, the fissile percent would become ~ 53%. Therefore, it is difficult to degrade the quality of weapons-grade plutonium by burning in MSR only, but the discharged fuel could be used as the reactor-grade plutonium. Though the increase of  $^{233}\text{Pa} + ^{233}\text{U}$  shows the tendency of saturation towards the end of 20 year period, the quantity of the increase of plutonium is rather accelerated towards the end of 20 year period. This is because the spectrum hardening due to the increase of the absorption of actinide isotopes. From the standpoint of plutonium burning, 4.66 times of initially loaded plutonium can be burnt in 10 years and 9.26 times in 20 years. However, considering the fact that the minimum of fissile percent appears at about 10 years, it seems unnecessary to burn plutonium more than 10 years.

#### 3.5.4. Calculation of toxicity

The main purpose of the present study is to see if it is possible to reduce the long-term toxicity by burning plutonium in a reactor system. For this purpose, the toxicities from the discharged fuel were calculated using ORIGEN-2 [9] code for the decay and build up of isotopes and DCI (dose coefficient of intake) [10]. As the first step, to check the appropriateness of the calculation method and data, the change in toxicities of the discharged fuel from a LWR was calculated for both the dose from water and that from air. These values were obtained by multiplying the DCI values to the activities calculated by ORIGEN-2 code and given in Siebert (Sv). The calculation was conducted both for the discharged fuel in Table 3.5.4 and for the case where 99% of plutonium isotopes were removed from the values in Table 3.5.4. Table 3.5.5, and Figs 3.5.5 and 3.5.6 show the results of the calculation. Though the value at 0 year of the case of 99% plutonium is removed in Fig. 3.5.5 looks extraordinary, this is due to  $^{239}\text{Np}$ . These results were compared at the IAEA's RCM in Taejon and it was confirmed that the method and the database are appropriate.

The same procedure was applied for the calculation of toxicities of discharged fuel after 10 and 20 years of burnup in a 200 MWth MSR. They are shown in Table 3.5.6 for reactor-grade plutonium and in Table 3.5.7 for weapons-grade plutonium, respectively. Comparing the results of 10 and 20 years of burnup for reactor-grade plutonium, it is found there is not much difference between 10 year and 20 year burnup except for the short period from discharge. The large difference in short period from discharge is mainly attributed to the increase in  $^{242}\text{Am}$  and  $^{244}\text{Cm}$ . The fact there are not much differences between the 10 year and 20 year burnup means there is some effect in reduction of the toxicity by burning plutonium longer in MSR. However, the quantity of reactor-grade plutonium burned in a MSR is not large and the decrease in the toxicity is small.

In the case of weapons-grade plutonium, the differences between the 10 and 20-year operation, respectively, are larger than the corresponding reactor-grade plutonium cases. This is because in weapons-grade plutonium the quantities of actinide isotopes rather increase rapidly near the end of 20 years of operation.

To make the comparison of the effectiveness of different fuel cycles, the following procedure was taken according to the agreement in the IAEA's RCM in Taejon. Since the annual output of plutonium from a 1 GWe LWR is 245 kg as shown in Table 3.5.4, and after the reprocessing 99% of that quantity is fed to the plutonium burning system. In our MSR system, the consumption of reactor-grade plutonium is 784.7 kg in 10 years and 1435.2 kg in 20 years, therefore, the annual requirement is 78.47 kg and 71.76 kg, respectively. Hence, to consume all the reprocessed plutonium produced in one 1 GWe LWR,  $245 \times 0.99 / 78.47 = 3.09$  units of 200 MWth MSR are required for the 10 year burnup case and  $245 \times 0.99 / 71.76 = 3.38$  units of the same MSR are required for the 20 year burnup case. Assuming the conversion efficiency of 40%, they produce 0.25 GW and 0.27 GW of electricity, respectively. Therefore, the doses from the combined fuel cycle can be calculated as  $(1-0.25) \times$  (values in Table 3.5.5 of 99% of plutonium removed) +  $3.09 \times$  (values in Table 3.5.6)/10 for case of the 10 year burnup case and  $(1-0.27) \times$  (values in Table 3.5.5 for 99% of plutonium is removed) +  $3.38 \times$  (values in Table 3.5.6)/20 for the 20 year burnup case. The results are shown in Table 3.5.8, and in Figs 3.5.7 and 3.5.8 together with the toxicities from the discharged fuel from LWR only. Except for the very long time ( $1.00 \times 10^7$  years from the fuel discharge) the dose from the combined system does not differ from that of LWR only. This is mainly due to the increased quantities of  $^{242}\text{Am}$  and  $^{244}\text{Cm}$  in the short period from the fuel discharge and  $^{229}\text{Th}$  that is the decay product of  $^{233}\text{U}$  for the long period from the fuel discharge. Although the case of 20-year burnup generally gives somewhat smaller doses for the longer period, the difference from the case of 10-year operation is very small. Thus, the reduction of toxicity by plutonium burning in MSR will not be expected even if we adopt the longer irradiation.

In the case of weapons-grade plutonium, as it is difficult to consider the corresponding reactor system as in the case of reactor-grade plutonium, we compared with the toxicities originated from the  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$  and  $^{232}\text{Th}$  which are loaded in the reactor as the fresh fuel as shown in Table 3.5.9. Because of the production of  $^{241}\text{Pu}$  and  $^{233}\text{U}$  which does not exist in the chain of the fresh fuel, the dose from the discharged fuel from MSR is very high until 100 years, and except for the points of  $1.0 \times 10^4$  and  $10 \times 10^7$  year the dose from both system are similar. The decrease at  $1.0 \times 10^4$  years is attributed to the burnup of  $^{239}\text{Pu}$  whose half-life is  $2.39 \times 10^4$  year, however, due to the build up of  $^{233}\text{U}$  and  $^{229}\text{Th}$ , the doses from the both system again become similar. Therefore, the reduction of toxicity is not hopeful by burning weapons-grade plutonium in MSR.

### 3.5.5. Conclusion

The burnup calculation up to 20 year was carried out for 200 MWth MSR loaded with both the reactor-grade plutonium and the weapons-grade plutonium. Also the toxicities from the discharged fuel at 10 years and 20-year burnup were calculated. It was shown that MSR with weapons-grade plutonium is able to burn 4.66 times of the initially loaded plutonium in 10 years and 9.26 times of that in 20 years. The corresponding values for MSR with reactor-grade plutonium are 1.43 times and 3.43 times, respectively. As for the quality of plutonium, the fissile percent of weapons-grade plutonium cannot be less than 60%; on the other hand, the fissile percent becomes almost 30%. That toxicity from the discharged fuel is normalized to the toxicity/year from the combined fuel cycle that produces 1 GWe of electricity for reactor-grade plutonium. It was found except for  $1.0 \times 10^7$  years, the toxicity from only LWR is smaller than that of combined system.

TABLE 3.5.1. ATOMIC NUMBER DENSITIES AT THE BEGINNING OF CALCULATION (n/cm<sup>3</sup>)

Nuclide	Reactor-grade	Weapons-grade
Th-233	3.649E-03	3.800E-03
Pu-238	1.908E-06	0
Pu-239	1.172E-04	5.920E-05
Pu-240	4.539E-05	3.780E-06
Pu-241	1.505E-05	0
Pu-242	9.531E-06	0
Li-7	2.260E-02	2.260E-02
Be-9	5.037E-03	5.037E-03
F-19	4.785E-02	4.785E-02
C-12	9.266E-02	9.266E-02

TABLE 3.5.2. MASSES OF PLUTONIUM AND U-233 (kg) (REACTOR-GRADE)

Burnup (years)	Pu-added		Pu at the end of interval			Pa-233 + U-233
	total Pu	fissile Pu	total Pu	Fissile Pu	fissile %	
0.32	291.7*	203.7*	279.5	189.5	0.678	6.4
0.6	29.2	20.3	297.1	196.6	0.662	12.5
0.91	29.2	20.3	312.5	197.7	0.633	64
1.26	23.3	16.3	315.2	192.2	0.610	29.1
1.62	23.3	16.3	314	186.3	0.593	38.1
2	20.4	14.3	312.6	177.7	0.568	46.8
2.4	20.4	14.3	311.8	169.5	0.544	55.2
2.71	20.4	14.3	311.4	162.3	0.521	62.9
2.98	20.4	14.3	314.8	156	0.496	69.9
3.29	20.4	14.3	318.2	153.7	0.483	75.4
3.66	20.4	14.3	318.8	151.7	0.476	80.4
4.09	20.4	14.3	319.4	147.3	0.461	86.1
4.54	20.4	14.3	320.9	143	0.446	91.4
5.02	20.4	14.3	322.2	140.1	0.435	96.3
5.54	20.4	14.3	325.4	137.1	0.421	100.8
5.98	20.4	14.3	328.6	136.1	0.414	104.6
6.46	20.4	14.3	332.3	135.1	0.407	108.3
6.94	20.4	14.3	335.8	134.8	0.401	111.6
7.41	20.4	14.3	339.4	134.4	0.396	114.7
7.87	20.4	14.3	343.1	134.1	0.391	117.7
8.26	20.4	14.3	332.9	134.1	0.403	120.5
8.79	20.4	14.3	347.9	133	0.382	123.3
9.32	20.4	14.3	350.9	132.1	0.376	126
9.71	20.4	14.3	352.5	130.9	0.371	130.7
10	20.4	14.3	351	130.6	0.372	133
Total up to 10 years						
Loaded Pu	784.7	548.5				
Burned Pu	433.7	417.9				
	initially loaded Pu *					

cont'd

TABLE 3.5.2. (MASSES OF PLUTONIUM AND U-233 (kg) (REACTOR-GRADE)

Burnup (years)	Pu-added		Pu at the end of interval			Pa-233 + U-233
	total Pu	fissile Pu	total Pu	fissile Pu	fissile %	
10.33	20.4	14.3	355.1	128.1	0.361	134.9
10.66	17.5	12.2	355	126.3	0.356	136.8
10.99	20.4	14.3	353	126.7	0.359	138.5
11.32	20.4	14.3	362.3	126.6	0.349	140.1
11.64	20.4	14.3	364.7	127	0.348	141.7
11.97	20.4	14.3	368.5	127.3	0.345	143.2
12.3	20.4	14.3	370.7	127.6	0.344	144.5
12.63	20.4	14.3	374.5	128.1	0.342	145.8
12.96	20.4	14.3	376.7	128.6	0.341	147
13.29	20.4	14.3	380.7	129	0.339	148
13.62	20.4	14.3	384.6	129.7	0.337	149.2
13.95	20.4	14.3	386.8	130.1	0.336	150.2
14.27	20.4	14.3	390.8	130.7	0.334	151.1
14.6	20.4	14.3	393	131.4	0.334	152
14.93	20.4	14.3	396.9	132	0.333	152.9
15.26	20.4	14.3	400.7	132.4	0.330	153.7
15.86	20.4	14.3	399.5	129.5	0.324	154.5
16.14	20.4	14.3	401.3	129.7	0.323	155.8
16.41	20.4	14.3	404.6	129.7	0.321	155.8
16.68	20.4	14.3	406.6	130	0.320	155.8
16.96	20.4	14.3	409.9	130.1	0.317	157.3
17.23	20.4	14.3	411.8	130.4	0.317	157.3
17.51	20.4	14.3	415.2	130.6	0.315	157.3
17.78	20.4	14.3	417	130.7	0.313	158.8
18.05	20.4	14.3	420.6	131.2	0.312	158.8
18.33	20.4	14.3	422.4	131.5	0.311	158.7
18.6	20.4	14.3	424.7	131.7	0.310	158.7
18.88	20.4	14.3	427.7	132.1	0.309	160.2
19.15	20.4	14.3	429.4	132.4	0.308	160.2
19.42	20.4	14.3	432.9	132.9	0.307	160.2
19.7	20.4	14.3	434.8	133.2	0.306	160.2
Total up to 20 years						
Loaded Pu	1435.2	1002.2				
Burned Pu	1000.4	869.0				

TABLE 3.5.3a. MASSES OF PLUTONIUM AND U-233 (kg) (WEAPONS-GRADE)

Burnup (years)	Pu-added		Pu at the end of interval			Pa-233 + U-233
	total Pu	fissile Pu	total Pu	fissile Pu	fissile %	
0	97.06*	93.8*	92.01	85.03	0.924	2.31
0.08	16.99	15.97	104	94.16	0.905	5.8
0.2	16.5	15.51	113.04	99.48	0.880	11.12
0.38	17.47	16.42	120.43	102.46	0.851	17.95
0.6	17.96	16.88	125.99	103.14	0.819	26
0.86	18.44	17.33	130.46	102.78	0.788	34.41
1.15	18.93	17.79	134.42	101.79	0.757	42.97
1.45	19.89	18.70	138.89	101.53	0.731	51.24
1.79	20.38	19.16	143.03	100.99	0.706	59.36
2.15	21.35	20.07	147.38	100.87	0.684	67.05
2.51	21.83	20.52	152.36	101.63	0.667	74.31
2.89	22.32	20.98	157.5	102.7	0.652	80.98
3.28	22.81	21.44	163.12	104.36	0.640	87.21
3.66	22.81	21.44	168.9	106.32	0.629	93.01
4.05	23.29	21.89	175.42	109.04	0.622	98.23
4.44	23.3	21.90	181.77	111.75	0.615	103.15
4.85	23.78	22.35	188.14	114.47	0.608	107.93
5.25	24.27	22.81	195.1	117.93	0.604	112.28
5.65	24.75	23.27	202.48	121.7	0.601	116.33
6.06	24.75	23.27	209.83	125.61	0.599	120.24
6.47	25.24	23.73	217.64	129.83	0.597	123.85
6.89	25.72	24.18	225.74	134.35	0.595	127.32
7.31	26.21	24.64	233.98	133.86	0.572	130.79
7.74	26.69	25.09	242.81	143.98	0.593	133.97
8.16	27.18	25.55	251.46	148.95	0.592	137.02
8.58	27.18	25.55	260.11	153.92	0.592	139.91
9.01	27.66	26.00	269.18	159.34	0.592	142.65
9.43	27.67	26.01	278.1	164.6	0.592	145.41
9.85	27.66	26.00	287.65	170.32	0.592	147.85
Total up to 10 years						
Pu-loaded	643.03	604.45				
Pu-burned	355.38	434.13				
	* initially loaded Pu					

(cont'd)

TABLE 3.5.3. MASSES OF PLUTONIUM AND U-233 (kg) (WEAPONS-GRADE)

Burnup (years)	Pu-added		Pu at the end of interval			Pa-233 + U-233
	total Pu	fissile Pu	total Pu	fissile Pu	fissile %	
10.28	27.67	26.01	297.21	176.19	0.593	151.05
10.7	27.66	26.00	306.62	181.76	0.593	152.48
11.13	28.15	26.46	316.49	176.19	0.557	155.39
11.55	28.14	26.45	325.46	193.05	0.593	156.81
11.97	28.14	26.45	336.23	199.82	0.594	159.71
12.4	28.15	26.46	345.5	205.24	0.594	161.15
12.82	28.63	26.91	356.12	212.01	0.595	164.05
13.25	28.63	26.91	365.39	217.73	0.596	165.5
13.67	28.63	26.91	376.02	224.05	0.596	166.94
14.09	28.63	26.91	385.44	229.47	0.595	169.84
14.52	28.63	26.91	396.22	236.24	0.596	171.27
14.94	28.63	26.91	405.34	241.51	0.596	172.72
15.37	29.11	27.36	416.11	248.28	0.597	174.16
15.79	29.12	27.37	427.05	255.05	0.597	175.6
16.21	29.12	27.37	436.32	260.05	0.596	177.05
16.64	29.12	27.37	446.65	267.25	0.598	179.95
17.06	29.11	27.36	458.34	274.02	0.598	181.4
17.47	29.11	27.36	467.16	279.28	0.598	182.85
17.89	29.11	27.36	477.47	286.06	0.599	184.29
18.3	29.12	27.37	489.33	292.83	0.598	185.74
18.72	29.12	27.37	499.52	299.6	0.600	187.16
19.13	29.11	27.36	508.33	304.87	0.600	188.63
19.55	29.12	27.37	520.03	311.64	0.599	190.08
19.96	29.11	27.36	530.37	318.4	0.600	190.06
Total up to 20 years						
Pu-loaded	1332.1	1252.17				
Pu-burned	801.73	933.77				

TABLE 3.5.4. DISCHARGE OF HEAVY METAL ISOTOPES (kg/year) FOR A TYPICAL PWR (NORMALIZED TO 1 GWE AND 300 FULL POWER DAYS)

U-234	4.51E+00
U-235	2.70E+02
U-236	1.07E+02
U-237	2.70E-01
U-238	2.69E+04
Np-237	1.11E+01
Np-239	2.27E+00
Pu-238	3.12E+00
Pu-239	1.43E+02
Pu-240	5.78E+01
Pu-241	3.11E+01
Pu-242	1.02E+02
Am-241	8.87E-01
Am-242m	1.66E-02
Am-242g	2.12E-03
Am-243	1.77E+00
Am-244	6.41E-05
Cm-242	2.38E-01
Cm-243	5.17E-03
Cm-244	4.56E-03
Cm-245	1.66E-02
Sum of Pu	2.45E+04
Σ	2.75E+04

TABLE 3.5.5. TOXICITIES/YEAR DUE TO DISCHARGED FUEL FROM A TYPICAL 1 GWe LWR

from water (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
discharged fuel	1.80E+10	1.48E+09	1.42E+09	1.16E+09	4.01E+08	1.28E+08	7.82E+06	1.48E+06	6.08E+05
99% of Pu removed	1.67E+10	2.59E+08	1.63E+08	5.37E+07	1.37E+07	4.71E+06	1.29E+06	8.59E+05	5.59E+05

from air (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
discharged fuel	4.39E+11	3.09E+11	2.79E+11	2.23E+11	7.26E+10	2.14E+10	1.17E+09	1.95E+08	5.91E+07
99% of Pu removed	2.16E+11	8.33E+10	4.17E+10	1.09E+10	2.56E+09	8.11E+08	1.25E+08	8.59E+07	4.59E+07

TABLE 3.5.6. TOXICITIES DUE TO DISCHARGED FUEL FROM 200 MWth MSR WITH REACTOR-GRADE PLUTONIUM

from water (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
10 year burnup	1.05E+10	5.35E+09	4.58E+09	2.32E+09	8.04E+08	2.22E+08	3.14E+07	2.43E+06	1.02E+05
20 year burnup	1.95E+10	1.20E+10	9.41E+09	2.95E+09	9.95E+08	2.91E+08	4.31E+07	3.59E+06	1.17E+05

from air (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
10 year burnup	1.38E+12	1.33E+12	1.09E+12	4.54E+11	1.46E+11	3.76E+10	5.19E+09	3.62E+08	1.87E+07
20 year burnup	3.61E+12	3.27E+12	2.48E+12	5.90E+11	1.81E+11	4.95E+10	6.83E+09	4.93E+08	2.20E+07

TABLE 3.5.7. TOXICITIES DUE TO DISCHARGED FUEL FROM 200 MW<sub>th</sub> MSR WITH WEAPONS-GRADE PLUTONIUM

from water (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
10 year burnup	8.27E+09	2.43E+09	2.13E+09	1.39E+09	5.54E+08	1.85E+08	3.47E+07	1.91E+06	8.36E+04
20 year burnup	1.25E+10	5.22E+09	4.45E+09	2.52E+09	1.02E+09	3.51E+08	5.09E+07	3.10E+06	1.35E+05

from air (Sv.)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
10 year burnup	8.02E+11	5.86E+11	4.75E+11	2.69E+11	1.00E+11	3.13E+10	5.72E+09	2.65E+08	1.67E+07
20 year burnup	1.62E+12	1.29E+12	1.03E+12	4.86E+11	1.82E+11	5.92E+10	8.22E+09	4.19E+08	3.06E+07

TABLE 3.5.8. TOXICITIES/YEAR DUE TO DISCHARGED FUEL COMBINED CYCLE OF LWR AND MSR WITH REACTOR-GRADE PLUTONIUM

from water (Sv)

year from discharge	0	1	10	100	1000	1.00E+04	1.00E+05	1.00E+06	1.00E+07
(a) 10 years MSR + LWR	1.58E+10	1.85E+09	1.53E+09	7.57E+08	2.59E+08	7.21E+07	1.07E+07	1.40E+06	4.51E+05
(b) 20 years MSR + LWR	1.55E+10	2.22E+09	1.71E+09	5.38E+08	1.78E+08	5.26E+07	8.23E+06	1.23E+06	4.29E+05
(c) LWR only	1.80E+10	1.48E+09	1.42E+09	1.16E+09	4.01E+08	1.28E+08	7.82E+06	1.48E+06	6.08E+05
(a) / (c)	0.88	1.25	1.08	0.65	0.65	0.56	1.37	0.95	0.74
(b) / (c)	0.86	1.50	1.20	0.46	0.44	0.41	1.05	0.83	0.71

from air (Sv)

year from discharge	0	1	10	100	1000	1.00E+04	1.00E+05	1.00E+06	1.00E+07
(a) 10 years MSR + LWR	5.88E+11	4.73E+11	3.68E+11	1.49E+11	4.70E+10	1.22E+10	1.70E+09	1.76E+08	4.02E+07
(b) 20 years MSR + LWR	7.69E+11	6.13E+11	4.50E+11	1.08E+11	3.25E+10	8.96E+09	1.25E+09	1.46E+08	3.72E+07
(c) LWR only	4.39E+11	3.09E+11	2.79E+11	2.23E+11	7.26E+10	2.14E+10	1.17E+09	1.95E+08	5.91E+07
(a) / (c)	1.34	1.53	1.32	0.67	0.65	0.57	1.45	0.90	0.68
(b) / (c)	1.75	1.98	1.61	0.48	0.45	0.42	1.07	0.75	0.63

TABLE 3.5.9. TOXICITIES FROM FRESH PLUTONIUM FUEL AND THOSE FROM DISCHARGED FUEL OF 200 MW<sub>th</sub> MSR WITH WEAPONS-GRADE PLUTONIUM

from water (Sv)

year from discharge	0	1	10	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06	1.00E+07
due to initially loaded Th-232	4.60E+03	6.23E+03	1.67E+04	2.41E+04	2.41E+04	2.41E+04	2.41E+04	2.41E+04	2.41E+04
due to initially loaded Pu	2.12E+08	2.12E+08	2.12E+08	2.10E+08	1.95E+08	9.95E+07	3.66E+06	2.03E+04	1.88E+04
due to added Pu to 10 years	5.15E+08	5.15E+08	5.15E+08	5.12E+08	4.93E+08	3.46E+08	2.35E+07	9.26E+04	9.11E+04
dose due to Pu (10 years) include Th series	7.27E+08	7.27E+08	7.27E+08	7.22E+08	6.88E+08	3.56E+08	2.72E+07	1.13E+05	1.10E+05
dose from discharged fuel	8.27E+09	2.43E+09	2.13E+09	1.39E+09	5.54E+08	1.85E+08	3.47E+07	1.91E+06	8.36E+04
due to added Pu to 20 years	1.13E+09	1.13E+09	1.13E+09	1.12E+09	1.08E+09	7.63E+08	5.21E+07	2.05E+05	2.01E+05
dose due to Pu (20 years) include Th series	1.34E+09	1.34E+09	1.34E+09	1.33E+09	1.28E+09	8.63E+08	5.58E+07	2.25E+05	2.20E+05
dose from discharged fuel	1.25E+10	5.22E+09	4.45E+09	2.52E+09	1.02E+09	3.51E+08	5.09E+07	3.10E+06	1.35E+05

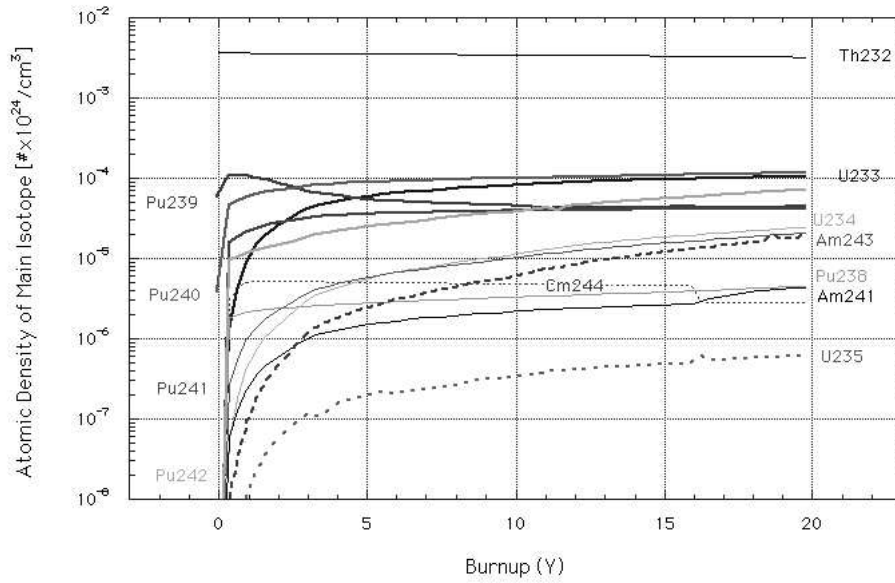


FIG. 3.5.5 Change of atomic density of main isotope with burnup time for MSR with reactor-grade plutonium.

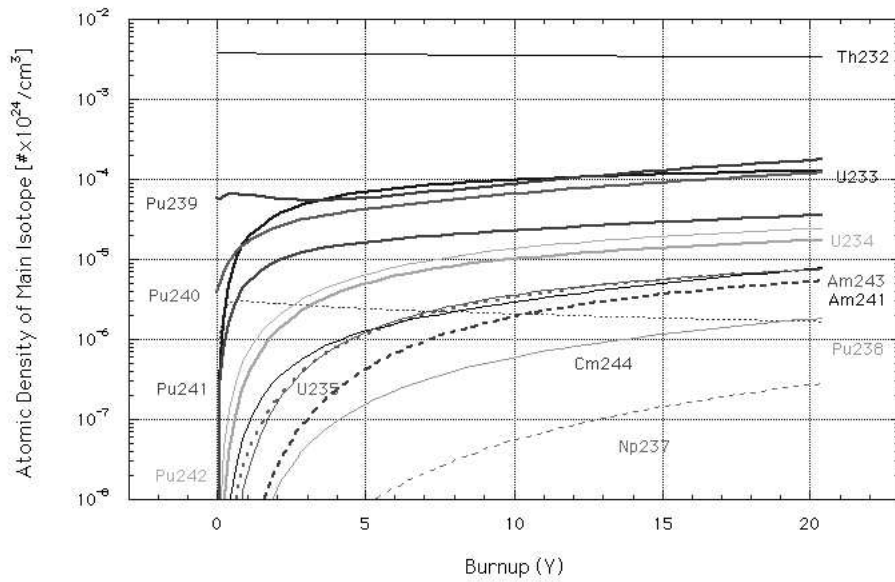


FIG. 3.5.6. Change of atomic density of main isotope with burnup time for MSR with weapons-grade plutonium.

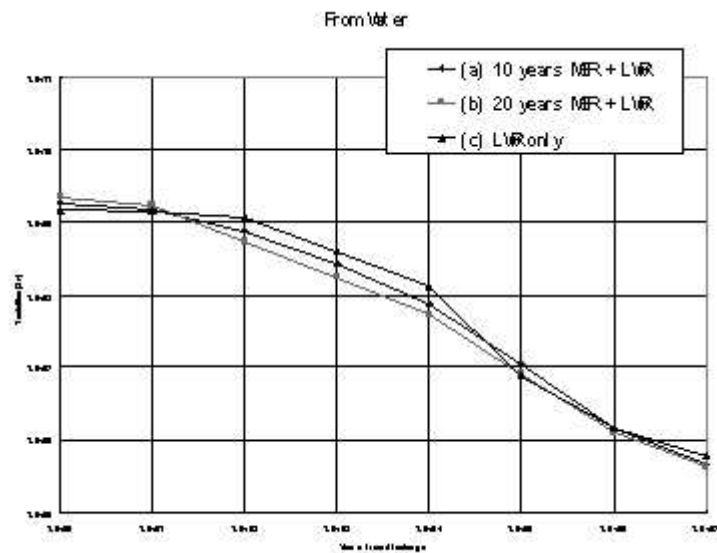


FIG. 3.5.7. Toxicities due to discharged fuel from combined fuel cycle of LWR and MSR with reactor-grade plutonium (DVI-W).

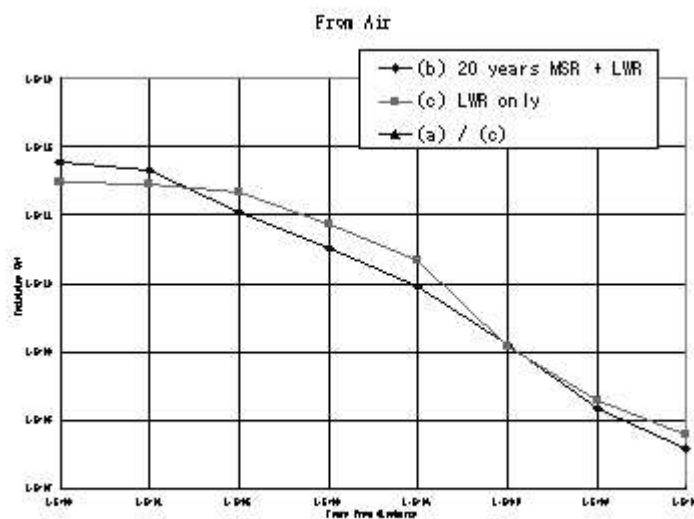


FIG. 3.5.8. Toxicities due to discharged fuel from combined fuel cycle of LWR and MSR with reactor-grade plutonium (DVI-A).

#### REFERENCES TO SECTION 3.5.

- [1] KASUMA, E., HIRAKAWA, N., Proc. Int'l Conf. Future Nuclear Systems (Global '93), Amer. Nuc. Soc. **1** (1993) 240.
- [2] MISAWA, T., OSAKA, M., YAMANE, Y., Proc. Int. Conf. Physics of Reactors (PHYSOR96) **4** M-127, Mito, Japan (1996).
- [3] MITACHI, K., et al., IAEA-TECDOC-840 (1995) 183-195.
- [4] ARKHIPOV, V., GALPERIN, A., RUTTEN, H.J., Proc. Int'l Conf. Emerging Nuclear Energy Systems **2** Tel Aviv, Israel (1999) 647-655.
- [5] ABOANBER, A.E., HIRAKAWA, N., MISAWA, T., MITACHI, K., ibid. **1** Tel Aviv, Israel (1999) 439-466.

- [6] FURUKAWA, K., et. al., J.Nucl. Sci. Technol. **27** No12 (1990) 1157.
- [7] HIRAKAWA, N., IWASAKI, T., SUYAMA, K., JAERI-DATA/Code, 97-047 (1997) (in Japanese).
- [8] KANEKO, K., OKUMURA, K., TSUCHIHASHI, K., JAERI-Data/Code, 96-015 (1996) (in Japanese).
- [9] CROFF, A.G., ORNL-5261 (1980).
- [10] RÜTTEN, H.J., Private communication (1998).